

# Heat Pipe Heat Transport System for the Stirling Space Power Converter (SSPC)

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## Heat Pipe Heat Transport System for the Stirling Space Power Converter (SSPC)

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### ABSTRACT

Life issues relating to a sodium heat pipe heat transport system are described. The heat pipe system provides heat, at a temperature of 1050 K, to a 50 kWe Stirling engine/linear alternator power converter called the Stirling Space Power Converter (SSPC). The converter is being developed under a National Aeronautics and Space Administration program. Since corrosion of heat pipe materials in contact with sodium can impact the life of the heat pipe, a literature review of sodium corrosion processes was performed. It was found that impurity reactions, primarily oxygen, and dissolution of alloy elements were the two corrosion processes likely to be operative in the heat pipe. Approaches that are being taken to minimize these corrosion processes are discussed.

### INTRODUCTION

A program is currently underway by the National Aeronautics and Space Administration to develop technology for the fabrication of the 50 kWe SSPC (1). The development of this converter is being performed under contract by Mechanical Technology Inc. (MTI). The SSPC will be designed with two opposed free-piston Stirling Engines, as shown in Figure 1, but only a 25 kWe converter, one-half of the 50 kWe SSPC, will be built and tested. A smaller version of the SSPC, the 12.5 kWe/piston Component Test Power Converter (CTPC), has been fabricated to develop technology for the SSPC (2). The heater head of both free-piston Stirling engines will operate at 1050 K. The CTPC has been fabricated from

Inconel 718 and has a relatively short design life; this power converter will prove all concepts to be incorporated in the final space version SSPC. The SSPC heater head will be made from Udimet 720 and has a design life of 60,000 hours. Both engines have sodium heat pipe heat transport systems.

This paper will focus upon life issues relating to the sodium heat pipe heat transport system for the SSPC. Each heat pipe of the SSPC will operate at 1050 K and will transport approximately 100 kW of heat into the engine's heater head. Udimet 720 alloy has been tentatively selected as the material for the SSPC heat pipe structure, but the material for the wick has not yet been chosen. Stainless steel (316L) material has been selected for the CTPC heat pipe wick. Approaches to minimize potential corrosion problems associated with these materials will be discussed. Dissolution and impurity reactions are the two corrosion processes that are likely to be operative in a sodium heat pipe.

### OXYGEN ENHANCED CORROSION

There was initial concern about the impurity reactions of elements of the Udimet 720 alloy with sodium. Although the word "impurities" can include oxygen, carbon, nitrogen and metallic trace elements such as silicon; oxygen was considered the major impurity of concern. Early in the SSPC program, liquid metal experts recommended that the oxygen level in the heat pipe be kept as low as possible (3 and 4). Following this advice, a literature search was carried out in an effort to better understand the problem. The search revealed overwhelming evidence that

oxygen is a major cause of corrosion in both heat pipe and flowing sodium loop systems. How a particular metal will behave in a sodium-oxygen environment will depend on the thermodynamic stability of the metal's oxide, at the particular temperature of interest, relative to sodium oxide.

Most of the sodium corrosion literature is related to the interaction of metal alloys of nuclear reactor systems with sodium. Much of this work was carried out during the 1960's and 1970's. A good review of this work is consolidated in several handbooks edited by Foust (5). Johnson, et al (6), pointed out that the presence of the oxygen impurity can be the controlling factor in many corrosion and mass-transfer processes. Considering only the impurity oxygen, how soluble is oxygen in sodium and how does it react with certain alloys to cause corrosion?

Eichelberger reviewed the literature for oxygen solubility in sodium and provided a recommended curve and equation relating the solubility of oxygen in sodium as a function of sodium temperature (7). Extrapolating from this curve, the solubility of oxygen in sodium at 1050 K is estimated to be 8100 ppm. In comparison, the solubility of metals in sodium is a few ppm. For example, at 1050 K, the solubility of nickel is approximately 4 ppm, chromium 6 ppm and iron 11 ppm (8). At this temperature, the solubility of molybdenum (9) and niobium (10) in sodium is less than 0.3 ppm.

The corrosion of Fe, Cr, Nb, Co and Nb by liquid sodium is a function of the oxygen concentration (6,11,12). Based on the free-energy data for oxides, the oxides of Fe, Ni, Nb, and Co are less stable than sodium oxide and will be reduced in sodium to form sodium oxide. Titanium and aluminum oxides are more stable than sodium oxide and will not be reduced by sodium (13,14).

One mechanism for the corrosion of metals in sodium by oxygen is by the formation of ternary oxides formed from sodium, oxygen and a metal. Although the solubility of metals is normally very low in sodium in comparison to oxygen, formation of a ternary oxide with sodium and oxygen effectively increases the solubility of the metal in sodium. Horsley first formed and identified the stable double oxide  $\text{FeO} \cdot (\text{Na}_2\text{O})_2$  (15). According to Gross and Wilson, about 1000

ppm of oxygen is needed to form  $\text{FeO} \cdot (\text{Na}_2\text{O})_2$  (16). Barker and Wood identified several ternary oxides on the surface of metals exposed to static sodium which contained dissolved oxygen (17). Ternary oxide compounds that were identified included:  $\text{Na}_3\text{NbO}_4$ ,  $\text{Na}_4\text{TiO}_4$ ,  $\text{NaCrO}_2$ , and  $\text{Na}_4\text{FeO}_3$ . Of the oxides identified, only  $\text{NaCrO}_2$  was observed as a strongly adherent compound. Their corrosion experiment showed that at low oxygen levels, of the order of 50 ppm, only sodium chromite,  $\text{NaCrO}_2$ , was found. At very high oxygen levels (0.73 to 4.28 wt.%) the chromite was present with the ternary oxide,  $\text{Na}_4\text{FeO}_3$ . Both chromium and iron ternary oxides have been found on surfaces of stainless steel in high-temperature, flowing sodium loops. (18,19). A molybdenum ternary oxide,  $\text{Na}_3\text{Mo}_2\text{O}_6$ , was formed in sodium at temperatures above 573 K (18).

Of the elements discussed thus far, nickel seems to stand alone as an element whose corrosion process is independent of oxygen. Gross and Wilson stated that a ternary oxide involving nickel, i.e., the double oxide  $\text{NiO} \cdot (\text{Na}_2\text{O})$ , cannot be stable in liquid sodium (16). Borgstedt and Frees found that corrosion rates of nickel specimens were unaffected by oxygen in the concentration range between 0.2 to 5 ppm (20). DeVan obtained data indicating that the mass transfer rate of Inconel X (85% nickel) in flowing liquid metal loops at 1089 K was not measurably affected by changes in the oxygen content of either sodium or NaK below 500 ppm (21). It is apparent that nickel corrosion occurs only by simple dissolution of the metal into the sodium.

## OXYGEN CAUSED FAILURE OF HEAT PIPES

Jacobson and Lou, following the postmortem examination of a failed heat pipe, concluded that the failure of the heat pipe resulted from the elevated contamination level of liquid sodium, in particular oxygen (22). In the post-failure analysis of another heat pipe, Jacobson and Wang concluded that the failure was caused by the combination of sodium-oxygen corrosion, liquid metal embrittlement and thermal stress corrosion (23). Lundberg and Feber, following postmortem analyses of molybdenum/sodium heat pipes, concluded that alkali heat pipes indicated impurity corrosion in their evaporators. The impurities that were observed to be transported included oxygen, carbon, and silicon (24).

## LOW-OXYGEN HEAT PIPE DESIGN APPROACH

As discussed, several heat pipe failures have been caused by the reaction of oxygen with metal atoms which produced corrosive products that eventually perforated the heat pipe wall. The obvious solution to this problem is to minimize the amount of oxygen in the heat pipe. One suggested method of obtaining a low level of oxygen in a heat pipe is to fill the heat pipe with sodium from a high purity sodium loop (4). The idea is to fill the heat pipe with high purity sodium, let it soak in sodium at a particular temperature for a period of time, then drain the sodium. This cycle is repeated several times. This process reduces unstable surface oxides and carries the resultant oxygen from the system yielding an oxide free surface.

Therefore, early in the program, three small cylindrical heat pipes were fabricated for the purpose of developing a heat pipe sodium filling process that used sodium from a high purity sodium loop. The detailed procedures for performing this process were prepared and carried out by Energy Technology Engineering Center (ETEC) personnel. They have since demonstrated that heat pipes can be loaded with sodium which contains a stable oxygen level of about 10 ppm. The ETEC sodium loop is capable of achieving an oxygen level of less than 1 ppm with refurbishment of the cold and hot traps. Therefore, it may be possible to achieve the sodium loading of a heat pipe which has an oxygen level lower than 10 ppm.

## DISSOLUTION

Even if corrosion by oxygen related mechanisms can be minimized, there remains the probability that some metal alloy components of Udimet 720 can dissolve directly into the sodium. In a heat pipe, the rate of dissolution of nickel and other metal constituents of Udimet 720 (nickel, chromium, etc.) depends upon the solubility of the metal in sodium and upon the flow rate of sodium between the evaporator and the condenser. For example, at 1050 K, the largest metallic constituent in Udimet 720, nickel, is soluble in sodium to a concentration level of about 4 ppm. The heat pipe will only contain a few grams of sodium and all of this sodium will be in close proximity to the large surface area presented by the wick. If the entire heat pipe is heated uniform-

ly to 1050 K, which means that there isn't any mass flow of sodium between the evaporator and the condenser, the small mass of sodium in the heat pipe will be saturated with nickel within about a minute. Once saturated, dissolution of nickel into the sodium will cease. This process is illustrated for the CTPC heat pipe, shown in Figure 2, by the following calculation. Although this heat pipe is actually fabricated from Inconel 718 and has a 316L stainless steel wick, for the purpose of this calculation, it will be assumed that both are made of pure nickel.

Non-operational, Uniformly Heated CTPC Starfish Heat Pipe - The dissolution rate for an element, for example nickel, from the metal surface into the sodium can be represented by the following equation (8,25).

$$dN/dt = k (N_0 - N(t)) \quad (1)$$

which integrates to

$$N(t) = N_0 (1 - e^{-kt}), \text{ where} \quad (2)$$

$N(t)$  = atoms of nickel in sodium of the CTPC heat pipe at any time,  $t$ , where

$t$  = time, sec, and

$N_0$  = atoms of nickel in sodium of the CTPC heat pipe at saturation at 1050 K, and

$$k = RA/N_0, \text{ where} \quad (3)$$

$R$  = dissolution rate of nickel atoms per second at 1050 K, and

$A$  = internal surface area of CTPC heat pipe,  $\text{cm}^2$ .

Based upon a CTPC heat pipe sodium loading of 610 grams ( $1.6 \times 10^{25}$  atoms) and a saturation value of 4 ppm for nickel (8) at 1050 K, saturated sodium will contain  $2.5 \times 10^{19}$  atoms of nickel. That is,  $N_0 = 2.5 \times 10^{19}$  atoms of nickel.

A measured nickel corrosion rate in a sodium loop at 873 K (20), as corrected to a temperature of 1050 K from data given in reference (26), was used as the dissolution rate,  $R$ .  $R = 2.85 \times 10^{13}$  nickel atoms/sec/ $\text{cm}^2$ . The measured sodium loop corrosion from references

(20) and (26), amounted to a loss of nickel from the surface at a rate of about 0.01 cm/yr (4 mils/yr).

The internal surface area of the CTPC heat pipe is approximately  $1 \times 10^5 \text{ cm}^2$ . This includes the surface of the heat pipe walls, the 2 layers of 100 mesh screen, and the 50 arteries which are made of 200 mesh screen. Therefore,

$$k = RA/N_0 = (2.85 \times 10^{13})(1 \times 10^5)/(2.5 \times 10^{19})$$

$$= 0.114, \text{ and}$$

$$N(t)/N_0 = 1 - e^{-0.114 t} \quad (4)$$

After a few substitutions for  $t$ , one soon learns that the sodium becomes 99.9% saturated with nickel in about one minute.

During Heat Pipe Operation - Once a temperature gradient is established between the evaporator and the condenser, fresh sodium vapor will continuously flow to the condenser and dilute the liquid sodium in the condenser. Therefore, the degree of saturation of the sodium of an operating heat pipe is dependent upon the mass transfer rate of the fresh sodium.

During heat pipe operation, sodium is continuously vaporized from the evaporator wick, condensed on the condenser surface, and returned to the evaporator as a liquid through the wick. The pure sodium vapor that condenses on the wick will dilute the nickel saturated liquid sodium, causing the heat pipe to be unsaturated with nickel during operation. A model will be setup to assess the behavior of the CTPC heat pipe in relation to the rate of nickel dissolution during heat pipe operation. Since the rate of corrosion of nickel from the condenser surface is of prime importance because the condenser walls are load bearing regions of the CTPC heat pipe, only the condenser portion of the heat pipe will be modelled.

The rate that nickel atoms dissolve into the condenser sodium from the nickel surface of the condenser can be described by equation (1), except that constants  $k$  and  $N_0$  must now reflect the condenser surface area and the amount of sodium that is contained in the condenser. That is,

$$dN(t)/dt = k_c (N_{oc} - N(t)) \quad (5)$$

$$\text{where } k_c = RA_c/N_{oc}, \text{ and} \quad (6)$$

$A_c$  = internal surface area of the CTPC heat pipe condenser,  $\text{cm}^2$ , and

$N_{oc}$  = atoms of nickel in sodium of the CTPC heat pipe condenser at saturation at 1050 K.

To estimate the rate that nickel atoms leave the condenser per unit of time, it is assumed that complete mixing of the nickel and sodium of the condenser will occur. It is further assumed that the sodium vapor from the evaporator condenses uniformly over the condenser surface. The following equation can then be written that describes the rate that nickel atoms leave the condenser.

$$d(N_{out}(t))/dt = (N_c(t)/(N_c(t) + S)) (dS/dt) \quad (7)$$

$$= (CPN_c(t)/(N_c(t) + S)), \text{ where}$$

$S$  = the number of sodium atoms in the condenser, and

$dS/dt$  = the rate that sodium atoms arrive at the condenser and is also the rate that sodium atoms are evaporated from the evaporator.

$dS/dt = CP$ , the rate that sodium is evaporated from the evaporator, where

$P$  = the thermal power input to the evaporator, Joules/sec, and

$C = 6.8 \times 10^{18}$  sodium atoms/Joule, which is calculated from the latent heat of vaporization,  $3.85 \times 10^3$  Joules/gram, for sodium at 1050 K.

A time-stepping code was written to perform the integration of these rate equations to compute  $N_c(t)$  according to the following equation.

$$(N_c(t))_i = \sum_{t=1}^{t=2} [(k_c(N_{oc} - (N_c(t))_i))dt -$$

$$(CP(N_c(t))_i / ((N_c(t))_i + S)dt]_{i=1}^{i=m} \quad (8)$$

For the first time increment,  $k_c$  was set equal to  $N_c(t)$  and a first value of  $N_c(t=1)_{i=1}$  was calculated for the first iteration,  $i = 1$ . This value was substituted into equation 8 and a new value of  $N_c(t=1)_{i=2}$  was calculated. This iteration process was continued until a constant value of  $N_c(t=1)_{i=m}$  was calculated after  $m$  iterations.  $N_c(t=1)_{i=m}$  was then substituted into equation 8 to compute the first value of  $N_c(t=2)_{i=1}$  for the second time increment. The process is then continued until  $t = n$ .

**Results** - At a heat pipe heat transfer rate of 50 kW, a steady state level of nickel in the condenser is reached in approximately 30 seconds at an  $N_c(t)/N_{oc}$  ratio of 0.638. At this steady state level, where nickel is being dissolved into the condenser at the same rate that nickel leaves the condenser, nickel passes through the condenser at a rate of  $3.4 \times 10^{17}$  atoms/sec. Based upon the CTPC heat pipe condenser surface area of  $3.298 \times 10^4 \text{ cm}^2$ , this corresponds to a loss of nickel from the surface at a rate of  $3.6 \times 10^{-3} \text{ cm/yr}$  (1.4 mils/yr). This is about one-third of the sodium loop corrosion rate, 0.01 cm/yr (4 mils/yr) presented in references (20) and (26) that was used to estimate the dissolution rate constant,  $R$ , given in equations (3 and (6). The calculation was repeated for power levels of 5 kW and 500 watts. As shown in Table I, the rate of nickel loss is nearly directly proportional to the power.

TABLE I

Estimated nickel corrosion rate for condenser for an all-nickel CTPC type heat pipe

Power kW	$N/N_0$	Nickel Corrosion Rate Atoms/sec	cm/yr (mils/yr)
0.5	0.9944	$5.30 \times 10^{15}$	$5.6 \times 10^{-5}$ (0.02)
5.0	0.9463	$5.05 \times 10^{16}$	$5.3 \times 10^{-4}$ (0.21)
50	0.6379	$3.40 \times 10^{17}$	$3.6 \times 10^{-3}$ (1.4)

## DISCUSSION OF DISSOLUTION RESULTS

In comparison to the corrosion rate for the sodium loop, 0.01 cm/yr (4 mils/yr), the computed heat pipe corrosion rates are much smaller. This is because the sodium in the condenser becomes partly saturated with nickel as shown by the  $N/N_0$  ratio in Table I. At the 50 kW design input power level for the CTPC heat pipe evaporator, a nickel corrosion rate of  $3.6 \times 10^{-3} \text{ cm/year}$  (1.4 mils/yr) is higher than desired for the long-life SSPC heat pipe, but still is acceptable with appropriate design modifications of the SSPC heat pipe. However, there is considerable heat pipe experimental data, discussed below, which suggests that the actual rate may be much lower. Furthermore, the analysis that has just been presented was done for pure nickel, not nickel alloy, and is based upon a number of assumptions. For example, there is experimental evidence which shows that dissolved nickel is not uniform over the thickness of the wick structure as assumed for this analysis, but that a nickel concentration gradient occurs over the wick thickness. Therefore, the analysis is meant to define a maximum probable nickel corrosion rate and to point out the need to measure actual corrosion rates in operating experimental heat pipes. This is the approach that has been planned, is underway, and will be discussed in the following paragraphs.

Pure nickel heat pipes have been operated for extensive periods of time without any indication of a mass transfer of nickel. DeVan and Jansen (27) performed a metallurgical examination of three pure nickel heat pipes, which included nickel wicks. The heat pipes had been operated at 873 K at a nominal power level of

1750 watts over a time period ranging from 6,000 to 10,000 hours. They concluded that mass transfer from the condenser did not occur to any significant extent. Although the working fluid in these heat pipes was potassium, it was stated in the report that potassium and sodium are very similar with regard to dissolution behavior. Harbaugh (28) reported the testing and metallurgical examination of another pure nickel heat pipe, also operated at 873 K at a nominal power level of 1750 watts, but for a time period of 21,000 hours. This heat pipe also contained potassium as the working fluid. No mass transfer of nickel occurred from the condenser of this heat pipe.

Other experimental evidence indicate that actual corrosion mechanisms that occur in heat pipes may be more complex than is described by equation (1). For example, Jacobson and Lou (22), during their post-test examination of an Inconel 600 heat pipe with a pure nickel wick, concluded that although there was a change in material composition of the heat pipe wall surface, the condenser region had not exhibited any noticeable corrosion during nearly 5000 hours of testing at 1144 K. The iron content decreased from 8% to 3.5%, the chromium content decreased from 15.5% to 4%, and the nickel content increased from 76% to 91%. That is, nickel had transferred radially from the pure nickel wick to the nominally 76% nickel Inconel 600 wall. Walak (29) experienced a similar phenomenon. As a part of the current SSPC development program, he operated an Inconel 718 heat pipe which was configured as a creep test specimen and tested for 1090 hours. The working fluid was sodium and the wick material was pure nickel. The heat pipe was operated over a temperature range between 1000 K and 1050 K. During post-test metallurgical examination of the Inconel 718 heat pipe condenser wall surface, Walak found that the iron content decreased from 19.03% to 13.76%, the chromium content decreased from 18.45% to 11.61%, and the nickel content increased from 52.1% to 69.19%. That is, nickel had also transferred radially from the pure nickel wick to the Inconel 718 condenser surface.

These experimental results point out the need, during modelling of the dissolution of heat pipe materials, to include the affect of differences in composition between wick and wall materials. As will be discussed later, it may be advantageous to intentionally have a higher content of

nickel in the wick in order to protect the heat pipe wall.

#### APPROACHES TAKEN TO ADDRESS POTENTIAL DISSOLUTION PROBLEMS

As discussed, three small, cylindrical Inconel 718 heat pipes were fabricated and used to define the sodium filling process. The wick material for these pipes was made from 316L stainless steel. One of these heat pipes was filled by a process which used commercial grade sodium. The other two pipes were filled with sodium by a newly defined process which used sodium from a low-oxygen sodium loop at ETEC. A similar Inconel 718 heat pipe has also been fabricated that contains a pure nickel wick. All of these heat pipes are being prepared for long-term testing. A ple-shaped heat pipe, one-tenth the size of the CTPC heat pipe, has been fabricated from Inconel 718 by MTI and is currently being cleaned and loaded with sodium by ETEC. The wicking of this heat pipe is also 316L stainless steel. At the conclusion of these tests, the heat pipes will be opened and metallurgically examined to look for corrosion and mass transfer. Similar, small, Udimet 720 heat pipes will also be fabricated and subjected to long-term testing followed by metallurgical analysis. All of the data obtained from the above mentioned heat pipe testing will be used for the final selection of materials for the SSPC.

The fins that make up the condenser region of the CTPC heat pipe have a surface area, less wick cover, that is less than 5% of the total internal surface area of the heat pipe. Although the fins constitute a small percentage of the condenser area, the fin surface is very critical because the fin is a load bearing member of the Stirling engine and must be fabricated from strong, high-temperature materials like Inconel 718 or Udimet 720. As shown in Figure 2, each fin contains gas passages which contain the high pressure helium working fluid at a nominal pressure of 15.0 MPa. During operation, the gas pressure fluctuates between about 13.5 to 16.5 MPa. The nominal wall thickness between this gas and the condenser wall is 0.75 mm. Because of the varying gas pressure, this wall is subject to fatigue failure. In addition, each fin is subjected to an axial tensile stress. As soon as it is understood how dissolution affects the superalloy heat pipes that are being tested, this information will



be used to determine methods to protect the fin wall from corrosion.

The data presented by Walak (29) presents an interesting possibility. If the wick is pure nickel, nickel will deposit on the nickel-base alloy (Inconel 718 or Udimet 720) condenser wall and protect the surface. On the other hand, one would expect that if the wick is stainless steel, nickel may transfer from the nickel alloy wall to the stainless steel wick thus depleting nickel from the nickel alloy condenser surface, an undesirable situation. The heat pipe testing previously discussed should help to clarify the best design approach.

The wick of a CTPC heat pipe constitutes about 85% of the total interior surface area of the heat pipe. Since the wick is not a load bearing part of the heater head and does not require high strength materials like Udimet 720, a wide range of materials is available for selection.

Finally, we are investigating the potential use of coatings to provide a barrier that may slow the rate of corrosion of the heat pipe materials. That is, such a coating will directly reduce the dissolution rate constant,  $R$ , used in equations (3) and (6). One material that is being considered is nickel aluminide. This material has been proven to be a very effective corrosion resistant coating for sodium loops in nuclear reactor applications (30).

## CONCLUSION

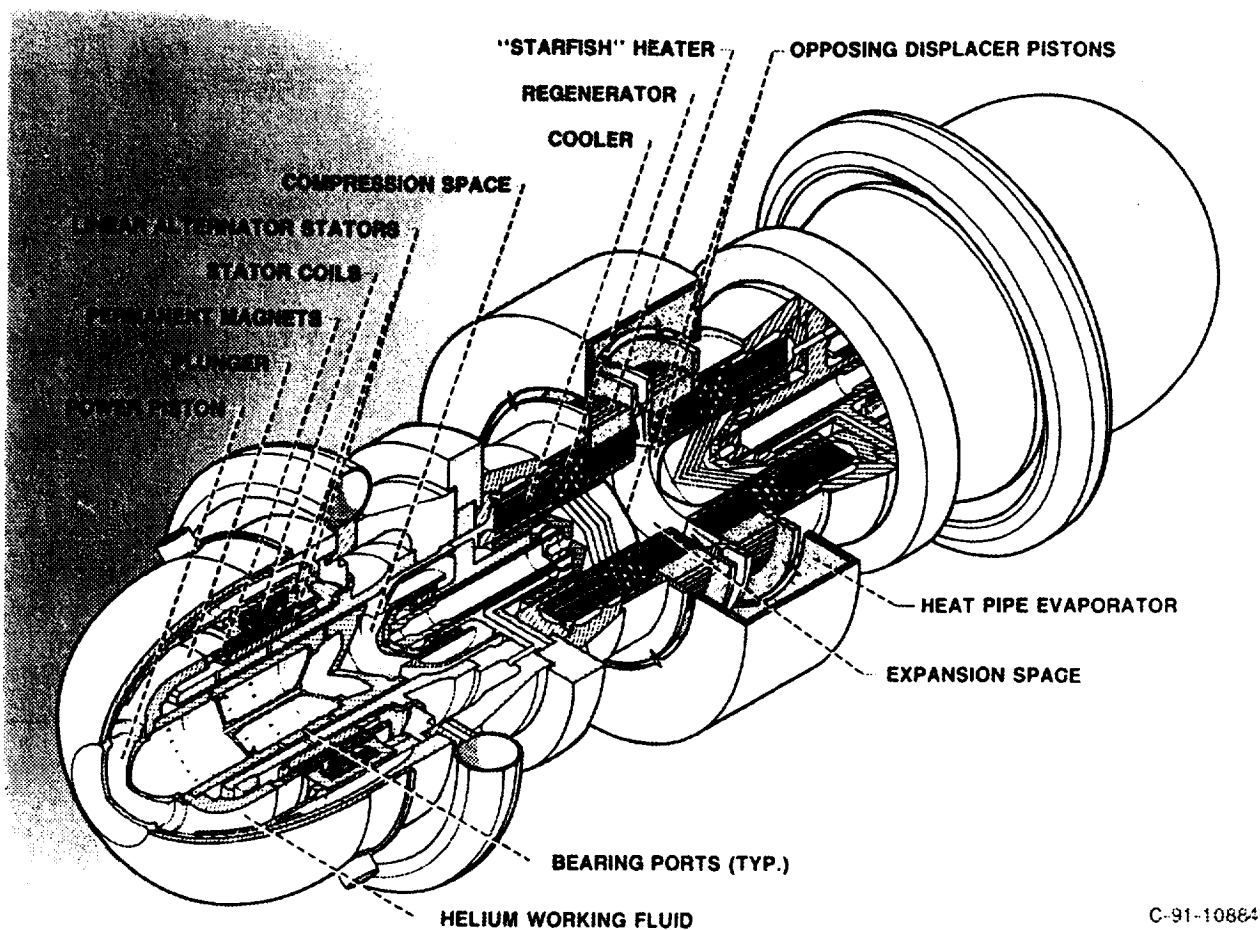
A literature search relating to the corrosion of nickel-base alloys by sodium was conducted. The results clearly indicate that the presence of impurities in the sodium, in particular, oxygen, can cause corrosion of the nickel-base alloy. Although the corrosion rate of most component elements of nickel-base alloys is dependent on the amount of oxygen contained in the sodium, corrosion of nickel is not oxygen dependent. It appears that corrosion of the nickel occurs by simple dissolution of the nickel into the sodium. The corrosion rate of nickel that has been measured in flowing sodium loop systems does not appear to apply to a heat pipe environment. Based upon the information gleaned from the literature search and simple analyses, heat pipe experiments have been planned to directly

measure corrosion rates in heat pipes. The results will be applied to the design of the final Stirling Space Power Converter.

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Figure 1.—Stirling space power converter.

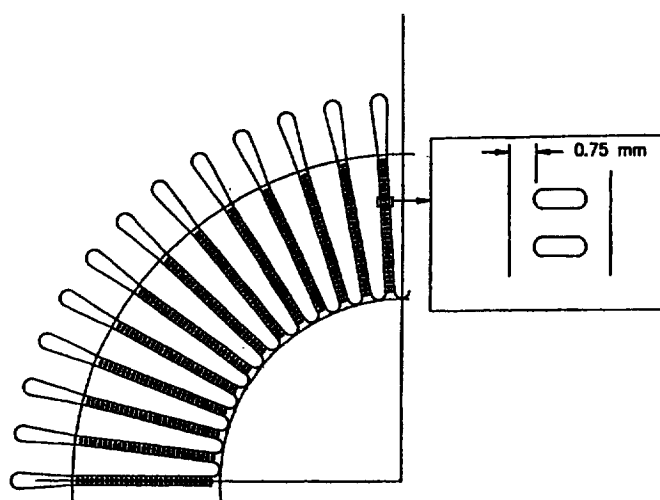


Figure 2.—Section view showing fins and condenser slot regions of CTPC Starfish heat pipe.

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